METHOD FOR DETERMINING TIME CONSTANTS OF A REFERENCE MODEL IN A CASCADE CONTROLLING CIRCUIT

The present invention relates to a method for determining at least one time constant of a reference model in a cascaded controlling arrangement in accordance with the preamble of claim 1.

Usually a cascaded controlling structure, consisting of a position, rpm and current control device, is employed in numerically controlled machine tools. As a rule, the speed control device, which is connected downstream of the position control device, is embodied as a PI speed control device and comprises a proportional branch (P) and an integral branch (I). The phase response of the upstream connected position control device worsens as a result of the effect of the integral branch of the speed control device. It is therefore necessary as a consequence of this to reduce the loop gain kV of the position control device a priori in order to prevent oscillations in the drive systems of the machine tool controlled by the controlling device. However, as large as possible a loop gain kV of the position control device is desired in principle.

To solve these problems, it has already been suggested by P. Ernst and G. Heinemann in the course of a seminar presentation under the title "Optimierte Achsregelung mit durchgängig offenen CNC-Steuerungen" [Optimized Axis Control with Continuously Open CNC Controls] (ISW Position Controlling Seminar 1999, 26, 03/27/1999) in Chapter 2.2 to connect a reference model upstream of the speed control device. The reference model, designed as a 2nd order time-delay element, is matched to the behavior of the closed speed control device without an integral portion. It is possible in this way to eliminate, or at least to minimize, the detrimental influence of the integral portion on the control behavior of the speed control device. However, the desired elimination of disturbances without integral portions continues to be fully maintained. However, no further suggestions can be found in the cited reference regarding suitable parameterization, in particular the determination of suitable time constants, of a corresponding 2nd order reference model.

It is therefore the object of the present invention to disclose a method for determining at least one time constant of a 2nd order reference model, which is arranged in a cascaded controlling device of a machine between a position control device and a speed control device, and which assures an optimized control behavior of the controlling device.

This object is attained by a method having the features of the characterizing portion of claim 1.

Advantageous embodiments of the method in accordance with the invention ensue from the steps in the dependent claims.

The parameterization of a suitable 2nd order reference model for the most varied types of machines is now possible by means of the method of the invention. Here, the resulting

reference model always assures that at least the undesired influence of the integral portion of the speed control device on the control behavior is eliminated.

Depending on the machine type, one time constant or two time constants are determined in accordance with the invention, which determine the behavior of the reference model and therefore affect the control behavior of the controlling arrangement during the actual controlling operation. However, in accordance with the invention at least the so-called second time constant of the reference model is basically determined as a function of a detected oscillation frequency of a continuous machine oscillation.

Surprisingly, or contrary to theoretical reflections, it is now possible by means of the steps of the invention for determining the time constant to also compensate controlled systems with idle times and delay elements for machines which theoretically would require higher order reference models; this applies in particular to the above mentioned category of non-rigid machines with dominant natural frequency. The determination of theoretically exact nth-order reference models ($n > 2$) in such machines would be connected with a very large outlay. In contrast to this it is possible by means of the use of second order time-delay elements as the reference model, whose time constants are determined in accordance with the invention, to keep the resulting outlay for parameterization of the reference model low.

The method in accordance with the invention can be performed manually, as well as in an automated manner.

Further advantages, as well as details of the method in accordance with the invention ensue from the subsequent description of exemplary embodiments by means of the attached drawings.

Shown here are in

FIG. 1, a block diagram representation of a part of a cascaded controlling structure of a numerically controlled machine tool,

FIGS. 2a and 2b, a flow diagram in each for explaining the determination in accordance with the invention of the time constant of a 2nd order reference model,

FIGS. 3 to 21, respectively different representations, which will be explained in greater detail in the ANNEX.

In a greatly schematized form, FIG. 1 shows a block diagram representation of a part of a cascaded controlling structure of a numerically controlled machine tool, such as is known, for example, in a similar shape from the above discussed reference.

The portion of the controlling structure represented comprises a position control device 10, as well as a downstream- connected speed control device 20. The actual controlled system 30 is arranged downstream of the speed control device 20 and is only schematically indicated. In the present example, the speed control device is embodied as a PI control device (proportional-integral control device); the integral branch 21, as well as the proportional branch

22 of the speed control device 20 are represented separately of each other in FIG. 1. A reference model 40 is arranged between the position control device 10 and the speed control device and is embodied as a 2nd order time-delay element, i.e. a so-called PT2 element. The reference model 40 simulates the behavior of the closed speed control device 20 without an integral portion and in this way assures that at least the undesired influence of the integral portion, or integral branch 21, on the control behavior of the speed control device is eliminated. As already indicated above, by means of the steps to be explained in what follows it is possible in a surprising manner to also parameterize reference models which compensate controlled systems with idle times and delay elements. In theory it would be necessary to parameterize reference models with orders $n > 2$ for such controlled systems, which would be relatively expensive.

The transfer function H(s) of the reference model 40 embodied as a 2nd order time-delay element results in a known manner from the following equation (1):

$$H(s) = K/(1 + T1 * s + (T2)^2 * s^2) \qquad \text{Equ. (1)}$$

The two time constants T1 and T2 are decisive for the layout, or the parameterization of the reference model 40. They must be determined as a function of the respective machine, or of the controlling conditions.

Contrary to theoretical considerations it has now been shown that the use of 2nd order reference models, whose time constants T1 and T2 are determined in accordance with the invention, is even possible when the respective system would actually have to be simulated by means of a reference model of higher order n, i.e. $n > 2$. However, the mathematically exact representation of such a complex system by means of an appropriate nth order reference model would basically cause an extremely high computational effort. In actuality this has the result that by means of the use of a 2nd order reference model, whose time constants T1 and T2 are determined by means of the invention, it is possible to also optimize the control behavior of the speed control device 20 for machines which are part of the second category already discussed above. Here, by employing a 2nd order reference model, which was parameterized in accordance with the invention, in these systems, not only is the influence of the integral branch of the speed control device eliminated, but moreover the influence of additional delays, or idle times, in the controlled system is also minimized. It is surprisingly possible to use loop gains kV in such systems with 2nd order reference models parameterized in accordance with the invention, which are greater than possible loop gains kV in case of a non-existing, or switched off integral branch in the speed control device.

The operation in accordance with the invention for determining the time constants T1, T2 for the 2nd order reference model will now be explained by means of the flow diagrams in

FIGS. 2a and 2b.

In the first part of the method explained in what follows, represented in FIG. 2a, first the time constant T2, or a correspondingly optimized value T2_OPT of the second time constant T2 will be determined.

In a first method step S10, first the determination, or presetting, of starting values $T1\_0_1$ and $T2\_0_1$ for the first and second time constant T1, T2 takes place. In the present example, the starting values $T1\_0_1$ and $T2\_0_1$ equaling $T1\_0_1 = O$ and $T2\_0_1 = 0$ are selected. This selection of the starting values $T1\_0_1$ and $T2\_0_1$ equaling $T1\_0_1 = O$ and $T2\_0_1 = 0$ means for the entire system in the end that the 2nd order reference model is switched out of the controlling arrangement, or is not active.

In what follows, the loop gain kV of the position control device is increased in steps in the following steps S20 and S30 and a check is made after each increase to determine whether an oscillation in the respective machine is already recognizable. This takes place until at a first maximum loop gain kV_{max1} an almost undamped oscillation of the machine at a defined oscillation frequency f_{S1} can be registered.

If an appropriate undamped oscillation of the machine can be registered, the associated oscillation frequency f_{S1} is measured, or determined, in accordance with the method step S40.

Thereafter, in the method step S50, the two optimized values T2_OPT and T1_OPT can be determined for the two time constants T1, T2. Here, the optimized value T2_OPT for the second time constant T2 can be determined as a function of the oscillation frequency f_{S1} determined in step S40, i.e.

$$T2\_OPT = f(f_{S1}) = 1 / (2 * \pi * f_{s1}) \qquad \text{Equ. (2)}$$

The optimized value T1_OPT for the first time constant T1 results from predetermined system parameters in accordance with the following equation:

$$T1\_OPT = (J_L * 2 * \pi) / (k_p * K_{MC}) \qquad \text{Equ. (3)}$$

wherein J_L: Momentary load,

k_p: Loop gain of the proportional branch of the speed control device,

K_{MC}: Motor constant.

Subsequently a check is performed in method steps S60 to S85 whether the previously determined time constants T1, T2 of the 2nd order reference model assure the desired control behavior during the controlling operation. Moreover, a maximum loop gain kV of the position

control device for the optimized time constants T1_OPT, T2_OPT is set in these method steps.

For this purpose, initially a check is made in the method step S60 whether an undamped oscillation of the machine results in the system when using the previously determined optimized values T1_OPT, T2_OPT and the first maximum loop gain kV_{max1} determined in step S30.

If this is not the case, the loop gain kV is increased by steps in method steps S70 and S80 until an undamped machine oscillation can be registered at a loop gain kV_{max2}. The maximum loop gain kV_{max2} determined in this way at which, in connection with the time constants T1_OPT, T2_OPT of the 2nd order reference model, an undamped machine oscillation occurs, is subsequently multiplied by a safety factor K < 1 in method step S85. From this then results the optimized loop gain kV_OPT for the position control device, which can be used for a stable system during controlling operations, i.e.

$$kV\_OPT = K * kV_{max2} \qquad \text{(Equ. 4)}$$

The safety factor K can be selected as K = 0.6, for example, in order to assure sufficient stability of the position control device in this way.

However, if it is found in method step S60 that, when using the previously optimized time constants T1_OPT, T2_OPT in the reference model and the loop gain kV_{max1}, an undamped machine oscillation already results at an oscillation frequency f_{S2}, the oscillation frequency f_{S2} is determined and an optimized time constant T2_OPT is again determined in method step S65 as a function of the oscillation frequency f_{S2} in accordance with

$$T2\_OPT = f(f_{S2}) = 1 / (2 * \pi * f_{S2}) \qquad \text{(Equ. 2')}.$$

If required, the determination of an optimized time constant T2_OPT is repeated several times in method steps S60 and S65, until finally no undamped machine oscillation can be registered at the selected parameters of T1_OP, T2_OPT.

In connection with machines of the first category, the second order reference model is basically parameterized after these steps, i.e. the two time constants T1 and T2 are determined. If it is intended to optimize the control structure of a machine of the second category, further method steps are required for suitably determining the first time constant T1 of the reference model in particular. This will be explained in what follows by means of FIG. 2b.

It is of course also possible to perform the following steps for determining a suitable first time constant T1 even with the mentioned machines of the first category in order to check in this way whether the value for T1_OPT set in accordance with the above Equ. (3) provides an acceptable system behavior.

Thus, for determining an optimized value T1_OPT' of the first time constant T1, first a second start value $T1\_0_2$ for the first time constant T1 is set in method step S90. For this, the value for T1 determined in step S50 in accordance with Equ. (3) is used as the second start value $T1\_0_2$, i.e. $T1\_0_2 = T1\_OPT$.

Thereafter the first time constant T1 is changed in method step S100, for example increased, and a check is subsequently made in method step S120 whether an undamped machine oscillation can already again be registered. Besides the increase of the first time constant T1 in step S100 it would basically also be conceivable that it be decreased.

As long as no undamped machine oscillation can be registered, the loop gain kV is increased in method steps kV up to a loop gain kV_{max3}, at which an undamped machine oscillation can be registered.

A check is thereupon made in method step S130, whether the loop gain kV_{max3} determined in this way is greater than the loop gain kV_{max2}, which had been maximal up to this time.

If the loop gain kV_{max3} is greater than the loop gain kV_{max2}, which had been maximal up to this time, the loop gain kV_{max3} is set to equal kV_{max2}, and a run-through of the method steps starting with S100 takes place again. This means that a check is made in the end whether with a changed value for T1_OPT a higher value for the loop gain kV can possibly be set.

This takes place until in method step S130 it is determined that the loop gain kV_{max3} is no longer greater than the loop gain kV_{max2} determined during the previous run- through.

In accordance with method step S140, the value for the first time constant T1 then present, besides the already previously determined value T2_OPT, is used as the optimized value T1_OPT for parameterizing the 2nd order reference model.

Furthermore, similar to the procedure in FIG. 2a, the last determined maximum loop gain kV_{max2} is multiplied by a correction factor $K < 1$, in order to again assure the stability of the position control device, i.e. the optimized value kV_OPT for the loop gain of the position control device again results as

$$kV\_OPT = K * kV_{max2} \qquad \text{Equ. (5)}$$

Thus, besides the two determined parameters T1 and T2 for the 2nd order reference model to be used, there is now also an optimized maximum loop gain kV_OPT for the position control device, which can be used in the subsequent controlling operation.

Alternative forms of embodiment also exist within the scope of the present invention.

The theoretical considerations on which the invention is based will be explained in greater detail in what follows in the following ANNEX and several simulations and test results will be presented.

ANNEX
(Theory, Simulation and Test Results)

1. Simulation with a Simplified Controlling Model

1.1 Model of the Controlled System

The method of the invention and the arrangement of the invention were tested by means of a mathematical simulation. This simulation which, besides the mathematical machine model, also contains the mathematical model of the invention, will be described in what follows.

The mass inertia moment of the controlled system, together with the momentary constants of the motor, are the defining characteristics of the system. The following parameters are used in connection with this:

Mass inertia $J_I = 50\ \mathrm{kgcm}^2$

Motor constant $k_{MC} = (1.5/\ \ 2) * (\mathrm{Nm}/A_{eff})$

Therefore, the controlled system G(s) is determined by:

$$G(s) = (num/den) = 1/(J * s)$$

The conversion from the radian frequency ω to U/s takes place by means of a downstream-connected P-element with 1/(2 * π). A disturbance can be introduced via the input "momentary disturbance Ms", which simultaneously affects the momentary value and the actual rpm. This is intended to correspond to a typical disturbance because of a milling cutter action and is used to rate the disturbance rigidity.

For simulating realistic rpm-connected losses, a derivative feedback k'p of the internal system output to the momentary summing point takes place. By means of this a new controlled system G'(s) is created:

$$G'(s) = (1/(J * s))/(1 + k'_p * (1/(J * s)))$$

$$G'(s) = (1/(k'_p\ + (J * s))$$

$$G'(s) = 1/k'_p * 1/(1 + (J/k'_p * s))$$

A TP1 control device is created by means of this derivative feedback.

A model of the 1st order controlled system with disturbance introduction is represented in FIG. 3.

1.2 Model of the Disturbed Controlled System

A model of the disturbed controlled system is represented in schematic form in FIG. 4. The controlled system is charged with a disturbance pulse of 2 Nm and of a length of 70 ms. The start time lies at 40 ms.

This disturbed controlled system is integrated into a simulation as a group "disturbed controlled system A -> U/s".

1.3 Simulation Model

The simulation model contains a closed position control device loop. For alignment purposes of the speed control device it is possible to introduce a skip of 200 mm/min to the speed control device via a switch 1. A suitable simulation model for examining a 1st order reference model is represented in FIG. 5. The IPC reference model can be switched on and off with the switch upstream of Sum 1.

2. Determination of the Simulation Parameters

It was necessary to determine the control device amplifications for parameterizing the control devices.

2.1 Alignment of the Speed Control device

For the alignment of the speed control device the disturbance moment of the controlled system was temporarily set to 0, and the switch 1 was set to skip. The skip size was 200 mm/min.

The conditions represented in FIG. 6 resulted for the loop gains for

P-factor (speed control device) = 9
I-factor (speed control device) = 2200

of the control device.

The simulation results correspond to a real drive mechanism. The control start time was set as Ta = 4.6 ms.

2.2 Determination of the Position Control Device Amplification kV

To determine the maximum position control device amplification, the I-portion of the speed control device was set to 0.

Position control device amplification = 15
P-factor (speed control device) = 9
I-factor (speed control device) = 0

The kV factor was set such that no oscillation of the actual motor current Iq occurred.

The low disturbance rigidity without the I-portion can be seen from the contour variation curve in FIG. 7. No complete removal of the disturbance takes place.

2.3 Activating the I-Portion of the Speed Control Device

The I-portion of the speed control device was activated without the position control device amplification being reduced.

Position control device amplification = 15
P-factor (speed control device) = 9
I-factor (speed control device) = 2200

In accordance with FIG. 8 it can be easily seen from the motor currents that the system oscillates. The kV factor (or the I-portion of the speed control device) must be reduced.

2.4 Reduction of the Position Control Device Amplification

The kV factor of the position control device was reduced until there was no longer a tendency to oscillate.

Position control device amplification = 9
P-factor (speed control device) = 9
I-factor (speed control device) = 2200

The contour variation increases (bad control behavior) because of the smaller kV factor, but the disturbance rigidity is improved in comparison with a system without an I-portion (see FIG. 9).

2.5 Series-Connection of the IPC Reference Model (1st Order) with the I-Portion

The kV factor, which in the beginning had been possible without the I-portion of the speed control device, was set. In addition, the I-portion of the aligned speed control device was set. The reference model was realized in the 1st order (neglecting the derivative loss feedback of the controlled system).

Position control device amplification MP1510 [m/min/mm] = 15 P-factor (speed control device)

MP2500 [As] = 9 I-factor (speed control device) MP2510 [A] = 2200

It is possible to read out of the diagram in FIG. 10, that with a low contour variation a large disturbance rigidity is provided.

3. Calculation of the IPC Reference Model

The basis for the reference model is that all portions of the P control device, including the system, do not reach the integrator. Therefore a simplified model of the closed control loop (only the P control device is active) was inserted into the set point default of the integrator. The motor losses are not considered.

3.1 Calculation from Model Parameters

The following physical values appear in this closes control loop:

P-factor speed control device: in [As/U]
Motor constant: kMC/sqrt(2) in [Nm/A]
Moment of mass inertia of the system Jl

Thus, the conversion function G(s) of the open control loop is:

$$G(s) = MP2500 * k_{MC} * 1/(2 * \pi) * 1/(J_l * s)$$

$k'_p = MP2500 * k_{MC} * 1/(2 * \pi)$

$G(s) = k'_p * 1/(J_I * s)$

The conversion function H(s) of the closed control loop is:

$H(s) = G(s)/(1 + G(s))$

$H(s) = (k'_p * 1/(J_I * s))/(1 + (k'_p * 1/(J_I * s)))$

$H(s) = 1/(1 + (J_I * s)/k_p')$

$H(s) = 1/(1 + T_I *s)$

A PT1 element with the time constant T1 is obtained as the IPC reference model:

$T_I = J_I /k_p' = (J_I *2 * \pi) /(MP2500 * k_{MC})$ (F1)

3.2 Calculation from Machine Parameters

Heidenhain controls have an acceleration feedforward control, which can be set by means of a machine parameter. This machine parameter MP26 provides the reciprocal value of the angular acceleration per current in [As2/U]. The time constant of the IPC can be calculated in a simple manner by means of the angular acceleration.

Mel = Electrical moment [Nm]
kMC = Momentary motor constant [Nm/A]
Jl = Moment of mass inertia [kg.m2]
MP26 = Acceleration feedforward control [As2/U]

$M_{el} = I_{MOT} * k_{MC}$

$\alpha = M_{el}/J_I$

$\alpha = (I_{MOT} * 2 * \pi)/MP26$

This is equal to:

$J_I/k_{MC} = (MP26)/2 * \pi$

This inserted in (F1):

$T_I = J_I / k_p' = (J_I * 2 * \pi) / (MP25 * k_{MC})$

$T_I = MP26/MP25$ (F2)

Although the IPC should be assigned to the integral factor of the speed control device, the IPC-MP should be among the feedforward control parameters, since it can only be used after MP26 has been determined.

4. Examination of the Phase Response of the Speed Control Device Loop

To examine the phase response, the phase shift of the closed speed control circuit is examined. A simulation model which contains, inter alia, the set point and actual speed, is used for this. The following phase responses were determined here.

4.1 Phase Response without IPC

The phase response without IPC is represented in FIG. 11. It can be seen that a limit in the phase does not result sooner than at -180°. A reduction of the phase edge results because of the I-portion of the speed control device, together with additional delays, idle times and large masses.

4.2 Phase Response with IPC

The phase response with IPC is represented in FIG. 12. With IPC the phase is only shifted by maximally -90°. Greater stability (or higher kV) of the position control device ensue because of the increase in the phase edge.

5. Consideration of the IPC in Feedforward Control

All previous reflections were made without feedforward controls (dragged operation). In what follows, the feedforward control will be included.

For reasons of clarity, the speed control device in the simulation model was realized in its own block and was equipped with the following inputs (from top to bottom):

Switching the IPC on or off

Switching the feedforward control on or off

Acceleration feedforward control from the interpolator (IPO)

Speed feedforward control from the IPO

Set point rpm

Actual rpm.

The speed control block has the following outputs:

Three signals (via a multiplexer) for monitoring the currents in the speed control device

Momentary current output Iq of the speed control device.

The structure of the position control device simulation with feedforward control is represented in FIG. 13. The speed feedforward control (Sum6) had additionally been integrated into the position control circuit.

By connecting the disturbance moment with the appropriate input of the controlled system, a disturbance can act as before on the controlled system.

The system allowance comes from the interpolator block (IPO). It is possible to perform a parameterization of jerk, acceleration, speed and distance via the Matlab dataset "M_IPO.M". "M_IPO.M" is also called up within "M_IPC.M".

5.1 Simulations of Following Errors

In what follows, the various feedforward controls are sequentially switched in. To compare the effects, all simulation parameters were kept constant.

System Parameters:

Momentary constant	Ktc[Nm/A]	= 1.5 * sqrt(2)
Momentary load inertia	Jl [kg.m2]	= 9
Rpm losses	[Nm/ω]	= 0.15

Control device circuit parameters:

Position control device amplification	MP1510 [m/min/mm]	= 9
P-factor (speed control device)	MP2500 [As]	= 9
I-factor (speed control device)	MP2510 [A]	= 2200

Interpolation parameters:

Jerk	r [m/s3]	= 2 * 103

Acceleration	a [m/s2]	= 5
Speed	v [m/s]	= 0.4 / 60
Position	s [m]	= 4 * 10-4

5.1.1 Following Error without Feedforward Control

The resulting following error without feedforward controls is represented in FIG. 14. A maximum following error of approximately 45 um results, which is impermissibly high.

5.1.2 Following Error with Speed Feedforward Control

The resulting following error without feedforward controls is represented in FIG. 15. A maximum following error during the acceleration phase of 10 um results.

5.1.3 Following Error with Acceleration Feedforward Control

The resulting following error with acceleration feedforward control is represented in FIG. 16. As can be seen, no following error can be shown.

5.1.4 Following Error with IPC (without IPC feedforward control)

The resulting following error with feedforward control and IPC (without IPC feedforward control) is represented in FIG. 17. As can be seen, a following error of 13 μm is built up at the end of the acceleration phase.

5.2 Installation of an IPC Feedforward Control into the Speed Control device

To reduce the following error during the acceleration phase it is necessary to implement an acceleration feedforward control. Since the input value of the IPC is a speed, a multiplication of the acceleration feedforward control a_soll(ipo) with the time constant T1 is necessary.

To make possible an implementation with optimized computing time, the feedforward control summing point was moved ahead from the control device output to the IPC input, the structure represented in FIG. 18 results in the process, i.e. IPC with acceleration feedforward control.

A further correction of the following error can be achieved by means of a jerk feedforward control. The feedforward control value "r_soll(ipo)" can be formed in the speed

control device by simple differentiation of "a_soll(ipo)". The time error of half a scanning time occurring in the process only plays a subordinate role.

The IPC with acceleration and jerk feedforward control is represented in FIG. 19.

5.2.1 Following Error with Convent. Feedforward Control, IPC and IPC Pilot Control

In the simulation the relevant feedforward controls were expanded with the above structure and compared with a structure wherein the feedforward control point is located at the control device output. No differences resulted here.

The resulting following error with conventional feedforward control, IPC and IPC feedforward control is represented in FIG. 20.

If the IPC feedforward control branch is installed, there is again no detectable following error.

The structure of the speed control device block with feedforward control in the control device output is represented in FIG. 21.

6. Practical Examination of the IPC

The practical examinations were performed on a DIGMA 700. Initially, a 1st order IPC, as had been employed in the above simulation, was implemented in the DSP software. Only small advantages result here when the IPC is used, the position control kv could only be increased by approximately 15%.

It was therefore necessary to use an IPC of higher order, which better corresponds to the real system conditions.

6.1 Use of a 2nd Order IPC

An implementation of the 2nd order IPC was used after the following conversion function:

$$H(s) = 1/(1 + (T_1 * s) + (T_2 * s^2))$$

This is the conversion function of a PT2 capable of oscillation with damping D.

$$D = \alpha/\beta = T_1/(2 * T_2)$$

A damped oscillation is to be expected in actual machine tools. Therefore, damping D moves in the range $0 < D < 1$.

The time constant T2 is calculated as follows:

$T_2 = T_1/(2 * D)$

Clearly improved results were already achieved with the use of a 2nd order IPC, however, they still did not approach the results of the simulation, which lead to conclusions of a theoretical increase of the position control amplification kv of approximately 170%. The following time constants were determined for the DIGMA 700:

Time Constants at DIGMA 700:

	X-axis	Y-axis	Z-axis
MP25	15	15	12
MP26	0.0212	0.0205	0.0165
T1'	1	1	1
T2'	0.0017	0.0018	0.0018
T1	1.41 ms	1.37 ms	1.37 ms
T2	1.7 ms	1.8 ms	1.8 ms
D	0.41	0.39	0.38

The below table shows the position control amplifications (kV factors) achieved at the X-axis of the DIGMA 700 in connection with various IPC designs. A search for the oscillation threshold was always performed here. In accordance with a rule of thumb, the latter must always be multiplied by a factor of 0.65 for stable operations.

	kV (Oscillation limit)	kV (stable)
Without IPC	8.5	5.5
1st order IPC	9.5	6.2
2nd order IPC (D=0.5)	13.0	8.5
2nd order IPC (D=0.41)	14.5	9.5

Thus, the position control amplification could be increased to 170%.

6.2 Derivation of the IPC Algorithm

The derivation of the IPC algorithm is based on the equation:

$H(s) = 1/(1 + (T1 * s) + (T2^2 * s^2)$

Determination of the T2 Time Constant

Tests with DIGMA 700 have shown that the T2 time constant, and therefore damping, is optimally set when the following error in the jerk phase showed a minimal deviation (with integrated jerk feedforward control). It was possible in this way to determine the T2 time constant for all three axes.

In the lab set-up (JL directly on the motor shaft) it was also possible to perform the determination of the optimum T2 time constant in this way.

Connection between Damping and T2 Time Constant

$D = T_1/(2 * T_2)$

6.3 Employment in Machines with Dominant Natural Frequency

A further employment option of the IPC is provided when in connection with machines with low natural resonance and insufficient damping the IPC time constants are matched to the controlled system.

In connection with first tests performed during production on the "Chiron FZ 22L" it was possible to increase the kV factor from 1 to 5. However, it was not possible in this case to use the time constant T1 determined from MP26 and MP25. It was necessary to employ a considerably higher time constant (approximately factor 5), which compensates a time constant in the machine.

In addition to "Chiron FZ 22L" a second machine, a Deckel- Mahon "DMU 50 V" was tested.

The Deckel-Mahon "DMU 50 V" machine has strong resonances at 42 Hz and 50 Hz. These are so dominant that it is only possible to set a jerk of 10 and an acceleration of 1.5 at kV = 4. By means of the use of the IPC it was possible to achieve a kV of 12 for all axes. The values for jerk could be increased to 20, acceleration was raised to 3.

Time Constants at DMU 50 V:

	X-axis	Y-axis	Z-axis
MP25	15	4.8	5.4
MP26	0.045	0.016	0.016

T1'	0.0042	0.0052	0.0052
T2'	0.003	0.0022	0.0013
T1	4.2 ms	5.2 ms	5.2 ms
T2	3.0 ms	2.2 ms	1.3 ms
D	0.70	1.18	2.00

The speed control device settings were not changed (original Deckel-Maho).

Result: A noticeable improvement in the position control device behavior could be achieved with both machines by the use of the IPC.

7. IPC Adjustment

When using the IPC it is necessary to differentiate between two types of machines. Type 1 is a rigid machine of not too large structural size, which is mostly directly driven or has linear motors. Type 2 is a machine with a dominant natural frequency in the range between 15 Hz to 80 Hz, in which no sufficiently large kV factor can be set.

7.1 Adjustment of Rigid Machines

With machines of the type 1 it is sufficient as a rule if the IPC is switched on with T1' = 1 and T2' = 0. The kV factor is increased until a noticeable oscillating tendency is noticed in the process.
Once this kV factor has been found, a fine adjustment of the IPC time constant T2 takes place. To this end first a T2 starting value of

T2 = 2/3 * MP26/MP25

is set. Thereafter T2' is changed until a new maximum kV factor has been found. Usually the T2 time constant must be reduced with this machine type (down to maximally 0.5 x the starting value). However, an increase with respect to the starting value is also conceivable.
At the end the kV factor for the oscillation threshold must be multiplied by the factor 0.65 in order to assure a sufficient stability of the position control device.
With this type of machine an increase of the kV by a factor of 1.4 to 1.7 is possible.

7.2 Adjustment of Machines with Dominant Natural Frequencies

With machines of the type 2, the same adjustment should initially be performed as with machine of the type 1. The IPC must be switched on with T1' = 1, and it is necessary to

determine T2. In this case it is also possible that a T2 time constant results which is clearly greater than the T2 starting value.

Now the T1 time constant must be determined. For this purpose a T1 starting value must be entered into MP2602 in place of a 1. It is calculated from

T1 = MP26/MP25

This starting value must be increased until a maximum kV factor has been found. If the found T1 time constant is clearly greater than the starting value (> factor 2), another adjustment of the T2 time component should take place. The value so far found should be lower, or raised, during testing.

Finally, the kV factor for the oscillation threshold must be multiplied by the factor 0.65 in order to assure a sufficient stability of the position control device.

With machines of the type 2 a greater increase of the kV than by the factor 1.7 is possible.